Neutrino Masses and TeV-scale Particles Testable at the LHC*

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Abstract

We consider a scenario in which TeV-scale particles belonging to weak-isospin multiplets higher than triplets lead to novel seesaw mechanisms different from conventional type I, II and III seesaw models. Besides an appealing testability of these mechanisms at the LHC, the model with Majorana quintuplets with imposed discrete symmetry may provide viable dark matter candidate.

1 Landmarks

The lightness of the neutrinos, the lightness of the Higgs boson and the evidence for a Dark Matter (DM) have been the landmarks for extensions of the particle content of the Standard Model (SM). Neutrino masses are the first tangible deviation from the SM so that the best motivated new particles appear in attempts to explain small neutrino masses. The most popular explanation is the so-called seesaw mechanism in which extremely small masses of neutrinos arise on account of inverse proportionality to large masses of new, yet to be discovered particles.

In the simplest, Type I seesaw model [1], new heavy particles are singlets under the Standard Model (SM) gauge group. Devoid of SM charges they do not feel SM forces and resemble the elusive substance contemplated by Rudjer Bošković long ago. In view of the 250th anniversary of the Venice-edition of his *Theoria* [2, 3], it seems timely to recall the prophetic thoughts in point No. 518 therein:
"It could be possible to imagine that there is no force between some of existing species. In this case, the substance of one kind might freely pass through that of another, without any collision. In the same way, two of the species might have a common force law with third species, without any force between the first two".

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The Type I seesaw mediators, as a substance without SM charges, would "pass through our matter without any collision". In order to discover them, it would be mandatory to assign to them a new charge (new gauge force) such as right-handed weak interaction.

Less elusive seesaw mediators seem to be those with nontrivial electroweak charges, as introduced in the remaining two [4] tree-level canonical seesaw mechanisms dubbed the type II [5] and type III [6]. Their scalar and fermion triplets allow for usual gauge invariant interactions with a neighbour SM-doublet state. This leads again to the Weinberg's [7] effective dimension-five operator $LL\Phi\Phi$, and relegates the masses of exotic seesaw mediators to remote $M \sim 10^{14}$ GeV of the GUT scale [8].

It is conceivable that Nature simply does not provide particles which are needed for type I, II and III mechanisms and that the first exotic particles we might encounter belong to the multiplets higher than the proposed triplets. Such higher multiplets would be related to dimension $d = 5+2n$ operators $(LL\Phi\Phi)(\Phi\Phi)^n$ studied in [9]. The corresponding light neutrino mass is given by the seesaw formula $m_\nu \sim v_H(v_H/M)^{d-4}$, where v_H= 246 GeV is the vev of the SM higgs. Accordingly, dimension-nine operators naturally correspond to TeV-scale new particles, within the discovery reach of the LHC.

2 Model with Dirac lepton quintuplet

In order to add something new to canonical tree-level seesaw mechanisms one can employ vectorlike fermionic multiplets with non-zero hypercharge. To generate a tree-level seesaw diagram, the hypercharge non-zero Dirac leptons have to be in conjunction with additional scalar fields.

Let us first systematize possible realizations of such tree-level mechanism [10, 11] and then focus to dimension-nine model realized with Dirac lepton quintuplet $\Sigma_{L,R} \sim (1,5,2)$. Since the sought-after higher-dimension operator can be relevant only in the absence of possible dimension-five operator, we forbid the existence of the states which may generate conventional seesaw mechanisms: a scalar triplet $\Delta \sim (1,3,2)$ generating type II seesaw, and a fermion singlet $N_R \sim (1,1,0)$ or triplet $N_R \sim (1,3,0)$ generating type I and III seesaw, respectively. Then, we are restricted to two options for seesaw mediators underlined in Table 1: the triplet fermions introduced in [12] and the quintuplet fermions proposed in [10, 11], in our focus here.

The model with Dirac lepton quintuplet starts from three generations of SM leptons L_L and l_R completed with n_Σ isospin $T=2$ vectorlike quintuplets with hypercharge two, $\Sigma_{L,R} \sim (1,5,2)$. Also, besides the SM Higgs doublet H there are two additional scalar quadruplets Φ_1 and Φ_2 transforming as $(1,4,-3)$ and $(1,4,-1)$,

$$\Sigma_{L,R} = \begin{pmatrix} \Sigma^{+++} \\ \Sigma^{++} \\ \Sigma^{+} \\ \Sigma^{0} \\ \Sigma^{-} \end{pmatrix}_{L,R} \quad ; \quad \Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^- \\ \phi_1^{--} \\ \phi_1^{---} \end{pmatrix} \quad , \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \\ \phi_2^- \\ \phi_2^{--} \end{pmatrix} . \tag{1}$$

Seesaw Type	Exotic Fermion	Exotic Scalar	Scalar Coupling	m_ν at
Type I	$N_R \sim (1,0)$	-	-	dim 5
Type II	-	$\Delta \sim (3,2)$	$\mu \Delta H H$	dim 5
Type III	$N_R \sim (3,0)$	-	-	dim 5
Conjunct Mediator	Exotic Fermion Pair	Exotic Scalars $\Phi_1,\ \Phi_2$	Scalar - Higgs Couplings	m_ν at
doublet	$\Sigma_{L,R}\ (2,1)$	$(3,-2),\ (3,0)$	$\mu_{1,2}\Phi_{1,2} H H$	dim 5
triplet	$\Sigma_{L,R}\ (3,2)$	$(4,-3),\ (2,-1)$	$\lambda_1 \Phi_1 H H H$	**dim 7**
quadruplet	$\Sigma_{L,R}\ (4,1)$	$(3,-2),\ (3,0)$	$\mu_{1,2}\Phi_{1,2} H H$	dim 5
quintuplet	$\Sigma_{L,R}\ (5,2)$	$(4,-3),\ (4,-1)$	$\lambda_{1,2}\Phi_{1,2} H H H$	**dim 9**

TABLE 1: The assignments of electroweak charges for exotic particles in case of Dirac seesaw mediators leading to the tree-level operators up to dimension nine.

Gauge invariant Lagrangian includes the Yukawa and Dirac mass terms

$$\begin{aligned} \mathcal{L} &= \overline{\Sigma_L} i D_\mu \gamma^\mu \Sigma_L + \overline{\Sigma_R} i D_\mu \gamma^\mu \Sigma_R - \overline{\Sigma_R} M_\Sigma \Sigma_L - \overline{\Sigma_L} M_\Sigma^\dagger \Sigma_R \\ &+ \left(\overline{\Sigma_R} Y_1 L_L \Phi_1^* + \overline{(\Sigma_L)^c} Y_2 L_L \Phi_2 + \text{H.c.} \right) . \end{aligned} \tag{2}$$

The scalar potential contains renormalizable terms relevant for our mechanism

$$\begin{aligned} V(H,\Phi_1,\Phi_2) &\sim -\mu_H^2 H^\dagger H + \mu_{\Phi_1}^2 \Phi_1^\dagger \Phi_1 + \mu_{\Phi_2}^2 \Phi_2^\dagger \Phi_2 + \lambda_H (H^\dagger H)^2 \\ &+ \{\lambda_1 \Phi_1^* H^* H^* H^* + \text{H.c.}\} + \{\lambda_2 \Phi_2^* H H^* H^* + \text{H.c.}\} \\ &+ \{\lambda_3 \Phi_1^* \Phi_2 H^* H^* + \text{H.c.}\} , \end{aligned} \tag{3}$$

where λ_1 and λ_2 terms induce vevs for the scalar quadruplets, which together with the Yukawa couplings define the matrix-valued couplings V_1 and V_2

$$v_{\Phi_1} \simeq -\lambda_1 \frac{v_H^3}{\mu_{\Phi_1}^2} \ , \ v_{\Phi_2} \simeq -\lambda_2 \frac{v_H^3}{\mu_{\Phi_2}^2} \ ; \ V_1 \sim Y_1^\dagger \frac{v_{\Phi_1}}{M_\Sigma} \ , \ V_2 \sim Y_2^\dagger \frac{v_{\Phi_2}^*}{M_\Sigma} \ . \tag{4}$$

2.1 Neutrino masses

The induced vevs v_{Φ_1} and v_{Φ_2} and the Yukawa terms in Eq. (2) lead to the mass terms connecting the SM lepton doublet with new Dirac quintuplet lepton. Three neutral left-handed fields ν_L, Σ_L^0 and $(\Sigma_R^0)^c$ span the symmetric neutral mass matrix as follows:

$$\mathcal{L}_{\nu\Sigma^0} = -\frac{1}{2} \left(\overline{(\nu_L)^c}\ \overline{(\Sigma_L^0)^c}\ \overline{\Sigma_R^0} \right) \begin{pmatrix} 0 & m_2^T & m_1^T \\ m_2 & 0 & M_\Sigma^T \\ m_1 & M_\Sigma & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ \Sigma_L^0 \\ (\Sigma_R^0)^c \end{pmatrix} + \text{H.c.} \ . \tag{5}$$

The diagonalization of this mass matrix leads to tree-level contribution to the light neutrino mass, and the quartic coupling λ_3 in Eq. (3) gives the loop contribution to the neutrino masses

$$m_\nu^{tree} \sim \frac{Y_1 Y_2\ \lambda_1 \lambda_2\ v_H^6}{M_\Sigma\ \mu_{\Phi_1}^2\ \mu_{\Phi_2}^2} \quad , \quad m_\nu^{loop} \sim \frac{Y_1 Y_2\ \lambda_3\ v_H^2}{16\pi^2\ M_\Sigma} \tag{6}$$

corresponding to dimension-nine tree-level seesaw mechanism and to dimension-five radiative mechanism displayed on LHS and RHS of Fig. 1, respectively.

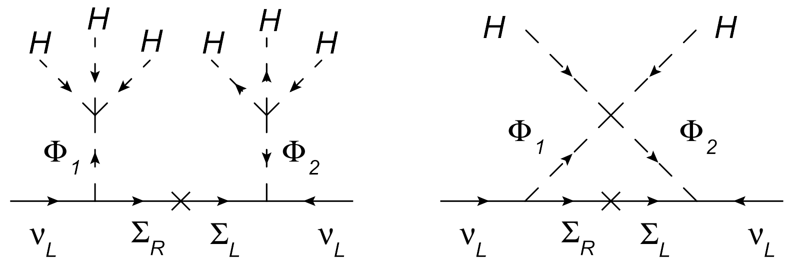

FIGURE 1: Tree-level diagram contribution (LHS) and one-loop diagram contribution (RHS) in Eq. (6).

2.2 Production and decays of Dirac quintuplet leptons at the LHC

The production channels of the heavy quintuplet leptons in proton-proton collisions, dominated by the quark-antiquark annihilation

$$q + \bar{q} \to A \to \Sigma + \bar{\Sigma} \, , \qquad A = \gamma, Z, W^{\pm} \, ,$$

are determined entirely by gauge couplings of neutral and charged gauge bosons. The cross sec-

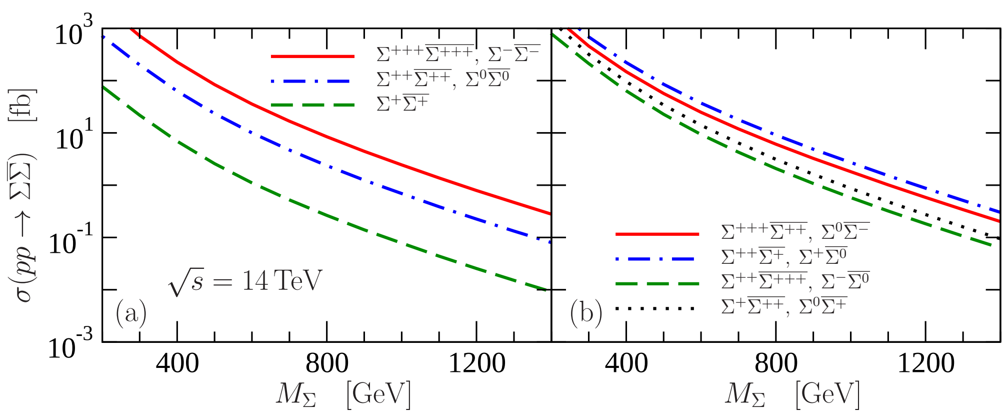

FIGURE 2: The cross sections for production of Dirac quintuplet lepton pairs on LHC proton-proton collisions at designed $\sqrt{s} = 14\,\mathrm{TeV}$ via neutral γ, Z (a) and charged $W^{\pm}$ currents (b), in dependence on the heavy quintuplet mass M_{Σ}.

tions for proton-proton collisions are presented for designed $\sqrt{s} = 14\,\mathrm{TeV}$ on Fig. 2. Thereby we distinguish the production via neutral currents shown on LHS and via charged currents shown on RHS of Fig. 2. By testing the heavy lepton production cross sections one can hope to identify the

quantum numbers of Dirac quintuplet particles, but in order to confirm their relation to neutrinos one has to study their decays. Provided that the exotic scalar states are slightly heavier than the exotic leptons, the exotic scalars will not appear in the final states in heavy lepton decays.

	$\overline{\Sigma^+} \to \ell^- Z^0$	$\overline{\Sigma^0} \to \ell^+ W^-$	$\overline{\Sigma^0} \to \ell^- W^+$	$\overline{\Sigma^-} \to \ell^+ Z^0$
$\Sigma^+ \to \ell^+ Z^0$	$\ell^+\ell^- Z^0 Z^0$	$\ell^+\ell^+ Z^0 W^-$	$\ell^+\ell^- Z^0 W^+$	-
$\Sigma^0 \to \ell^- W^+$	$\ell^-\ell^- W^+ Z^0$	$\ell^-\ell^+ W^+ W^-$	$\ell^-\ell^- W^+ W^+$	$\ell^-\ell^+ W^+ Z^0$
$\Sigma^0 \to \ell^+ W^-$	$\ell^+\ell^- W^- Z^0$	$\ell^+\ell^+ W^- W^-$	$\ell^+\ell^- W^- W^+$	$\ell^+\ell^+ W^- Z^0$
$\Sigma^- \to \ell^- Z^0$	-	$\ell^-\ell^+ Z^0 W^-$	$\ell^-\ell^- Z^0 W^+$	$\ell^-\ell^+ Z^0 Z^0$

TABLE 2: Decays to SM particles including same sign dilepton events

Pointlike decays to gauge bosons and SM leptons are experienced by four lowest states out of the five Σ-states properly ordered in Eq. (1). In Table 2 we list all possible events coming from the decays of the neutral and singly-charged Dirac quintuplet states to the SM charged leptons. This includes the same-sign dilepton events as a distinguished signature at the LHC.

The partial decay width of Σ^{++} state decaying exclusively via a charged current is

$$\Gamma(\Sigma^{++} \to \ell^+ W^+) = \frac{g^2}{32\pi} \left| \sqrt{3} V_2^{\ell\Sigma} \right|^2 \frac{M_\Sigma^3}{M_W^2} \left(1 - \frac{M_W^2}{M_\Sigma^2} \right)^2 \left(1 + 2 \frac{M_W^2}{M_\Sigma^2} \right) . \quad (7)$$

There is no such pointlike decay of the triply-charged Σ^{+++} state which has other interesting decays presented below.

Cascade decays $\Sigma^i \to \Sigma^j \pi^+$ and $\Sigma^i \to \Sigma^j l^+ \nu$ are suppressed by small mass differences, except for Σ^{+++} decays. These decays will serve as the referent decays for the golden decay mode of the triply-charged state.

Golden decay mode $\Sigma^{+++} \to W^+ W^+ l^+$ given by partial width plotted on Fig. 3, $\Gamma(\Sigma^{+++} \to W^+ W^+ l^+) \sim M_\Sigma^5 / M_W^4$ in the limit $M_\Sigma \gg M_W$, is governed by the same mixing factor V_2 which determines the Σ^{++} decay in Eq. (7). On the same figure we plot the partial widths for other decays of Σ^{+++}. For $5\ \mathrm{fb}^{-1}$ of integrated luminosity of 2011 LHC run at $\sqrt{s} = 7$ TeV and $21\ \mathrm{fb}^{-1}$ of integrated luminosity of 2012 LHC run at $\sqrt{s} = 8$ TeV, there could be 8000 Σ-$\overline{\Sigma}$ pairs in total produced for $M_\Sigma = 400\,\mathrm{GeV}$. There are 3300 triply-charged Σ^{+++} or $\overline{\Sigma^{+++}}$ fermions among them, resulting in ~ 300 golden decays $\Sigma^{+++}(\overline{\Sigma^{+++}}) \to W^\pm W^\pm l^\pm$. This makes the model with Dirac quintuplet falsifiable at the LHC. A mere nonobservance of triply-charged Dirac fermions would put a study of Majorana quintuplet in a forefront.

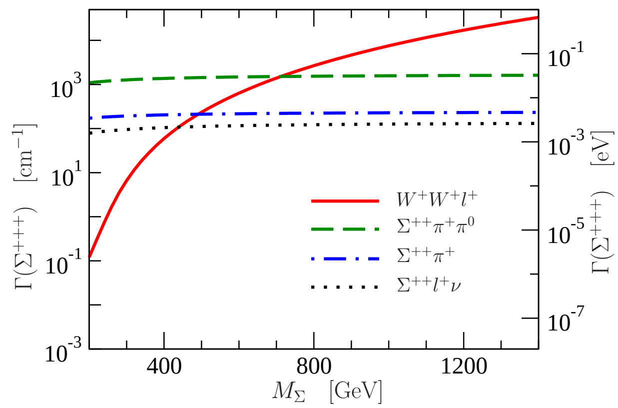

FIGURE 3: Selected partial decay widths of Σ^{+++} Dirac quintuplet lepton for $|V_2^{l\Sigma}| = 10^{-6}\sqrt{\frac{800}{M_\Sigma(\mathrm{GeV})}}$ in dependence of heavy quintuplet mass M_Σ.

3 Model with Majorana Quintuplets

This model [13] adds to SM fermions three generations of hypercharge zero lepton quintuplets $\Sigma_R = (\Sigma_R^{++}, \Sigma_R^{+}, \Sigma_R^{0}, \Sigma_R^{-}, \Sigma_R^{--})$, transforming as $(1,5,0)$ under the SM gauge group. Also, in addition to SM Higgs doublet $H = (H^+, H^0)$ there is a scalar quadruplet $\Phi = (\Phi^+, \Phi^0, \Phi^-, \Phi^{--})$ transforming as $(1,4,-1)$.

The gauge invariant and renormalizable Lagrangian involving these new fields reads

$$\mathcal{L} = \overline{\Sigma_R} i\gamma^\mu D_\mu \Sigma_R + (D^\mu\Phi)^\dagger(D_\mu\Phi) - \left(\overline{L_L} Y \Phi \Sigma_R + \frac{1}{2}\overline{(\Sigma_R)^C} M \Sigma_R + \mathrm{H.c.}\right) - V(H,\Phi)\,. \quad (8)$$

Here, Y is the Yukawa-coupling matrix and M is the mass matrix of the heavy leptons, which contains the terms containing two charged Dirac fermions and one neutral Majorana fermion

$$\Sigma^{++} = \Sigma_R^{++} + \Sigma_R^{--C}\,,\ \Sigma^{+} = \Sigma_R^{+} - \Sigma_R^{-C}\,,\ \Sigma^{0} = \Sigma_R^{0} + \Sigma_R^{0C}\,. \quad (9)$$

The scalar potential, assuming real quartic couplings, has the gauge invariant form

$$\begin{aligned} V(H,\Phi) &= -\mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger\Phi + \lambda_1\left(H^\dagger H\right)^2 + \lambda_2 H^\dagger H \Phi^\dagger\Phi + \lambda_3 H^* H \Phi^* \Phi \\ &+ \left(\lambda_4 H^* H H \Phi + \mathrm{H.c.}\right) + \left(\lambda_5 H H \Phi\Phi + \mathrm{H.c.}\right) + \left(\lambda_6 H \Phi^* \Phi\Phi + \mathrm{H.c.}\right) \\ &+ \lambda_7\left(\Phi^\dagger\Phi\right)^2 + \lambda_8 \Phi^*\Phi\Phi^*\Phi\,. \end{aligned} \quad (10)$$

The presence of the λ_4 term leads to the induced vev $v_\Phi \sim -\lambda_4 v_H^3/\mu_\Phi^2$.

3.1 Neutrino masses

The vev v_Φ generates a Dirac mass term connecting ν_L and Σ_R^0, a nondiagonal entry in the mass matrix for neutral leptons given by

$$\mathcal{L}_{\nu\Sigma^0} = -\frac{1}{2}\left(\overline{\nu_L}\ \overline{(\Sigma_R^0)^C}\right)\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} Y v_\Phi \\ \frac{1}{\sqrt{2}} Y^T v_\Phi & M \end{pmatrix}\begin{pmatrix} (\nu_L)^c \\ \Sigma_R^0 \end{pmatrix} + \mathrm{H.c.}\,. \quad (11)$$

After diagonalizing this mass matrix the light neutrinos acquire the Majorana mass contribution corresponding to tree-level diagram displayed on LHS of Fig. 4. Simultaneously, the quartic λ_5 term in Eq. (10) generates the one-loop diagram displayed on RHS of Fig. 4. These two

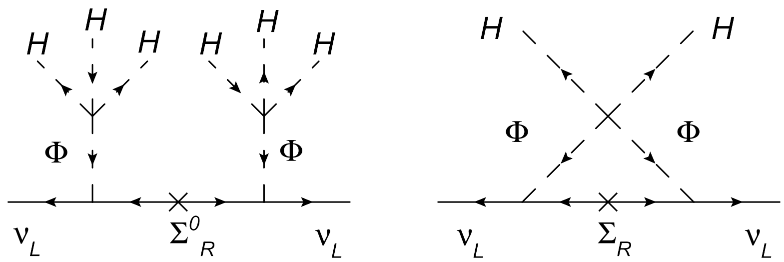

FIGURE 4: Tree-level diagram corresponding to dimension-nine operator and one-loop diagrams corresponding to dimension-five operator.

contributions added together give the light neutrino mass matrix

$$
\begin{aligned}
(m_\nu)_{ij} &= (m_\nu)^{tree}_{ij} + (m_\nu)^{loop}_{ij} \\
&= \frac{-1}{6}(\lambda_4^*)^2 \frac{v^6}{\mu_\Phi^4} \sum_k \frac{Y_{ik}Y_{jk}}{M_k} + \frac{-5\lambda_5^* v^2}{24\pi^2} \sum_k \frac{Y_{ik}Y_{jk}M_k}{m_\Phi^2 - M_k^2}\left[1 - \frac{M_k^2}{m_\Phi^2 - M_k^2}\ln\frac{m_\Phi^2}{M_k^2}\right] .
\end{aligned}
\tag{12}
$$

3.2 Production and decays of Majorana quintuplet leptons at the LHC

The production channels of heavy quintuplet leptons in proton-proton collisions are dominated by the quark-antiquark annihilation via neutral and charged gauge bosons.

On Fig. 5 we plot the expected number of produced Σ^{++} and $\overline{\Sigma^{++}}$ particles for three characteristic collider setups. In particular, for $M_\Sigma = 400\,\mathrm{GeV}$ and $5\ \mathrm{fb}^{-1}$ of integrated luminosity of 2011 LHC run at $\sqrt{s} = 7$ TeV, and $21\ \mathrm{fb}^{-1}$ of integrated luminosity of 2012 LHC run at $\sqrt{s} = 8$ TeV, there should be about 3200 doubly-charged Σ^{++} or $\overline{\Sigma^{++}}$ fermions produced. In total, there should be 4000 $\Sigma - \overline{\Sigma}$ pairs produced.

In order to confirm the relation of the quintuplet particles to neutrinos one has to study their decays. We list the representative final states of these decays in Table 3, which includes same-sign dilepton events as distinguished signatures at the LHC. The distinctive signatures could come from doubly-charged components of the fermionic quintuplets. The signals which are good for the discovery correspond to relatively high signal rate and small SM background. Two promising classes of events contain Σ^+ decaying to e^+ or μ^+ lepton and $Z^0 \to (\ell^+\ell^-, q\bar{q})$ resonance helping in Σ^+ identification:

$$(i) \qquad p\,p \to \Sigma^+\,\overline{\Sigma^0} \to (\ell^+ Z^0)\,(\ell^+ W^-)\ ,$$

the LNV event having 0.7 fb with the same-sign dilepton state, which is nonexistent in the SM and thus devoid of the SM background;

$$(ii) \qquad p\,p \to \Sigma^{++}\,\overline{\Sigma^{+}} \to (\ell^+ W^+)\,(\ell^- Z^0)\ ,$$

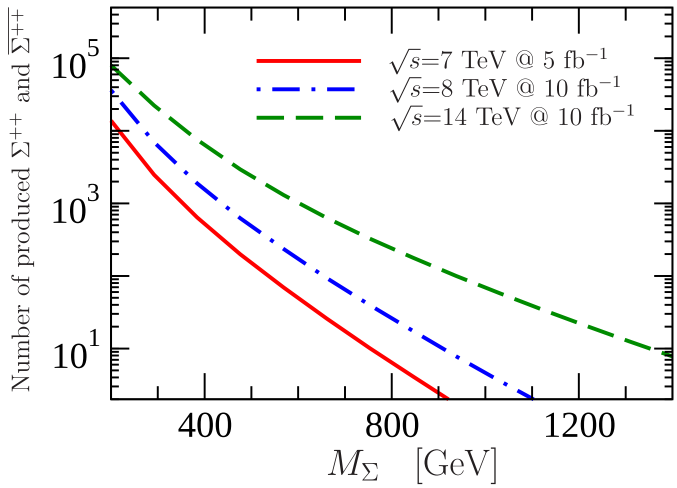

FIGURE 5: Number of Σ^{++} and $\overline{\Sigma^{++}}$ particles produced for three characteristic LHC collider setups, in dependence on the heavy lepton mass M_Σ.

having relatively high signal rate of 1.1 fb with respect to the SM background of 0.8 fb.

3.3 Higgs diphoton-decay induced by doubly-charged scalars

The recent discovery of a Higgs-like boson at the Large Hadron Collider (LHC) may mark an onset of a new set of particles with mass at the 100 GeV scale. Simultaneously, a "virtual physics" in the LHC era may have important effects in rare, loop-induced processes.
We have considered [14] the possible enhancement of the $h \to \gamma\gamma$ decay rate through extra contributions with charged components of scalar quadruplet Φ running in the loops, additional to dominant SM contributions from the W boson and top quark loops. The analytic expression for the diphoton $h \to \gamma\gamma$ partial width reads [15]

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v_H^2} \left| A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t) + N_{c,S} Q_S^2 \frac{c_S}{2} \frac{v_H^2}{m_S^2} A_0(\tau_S) \right|^2 , \tag{13}$$

where the three contributions corresponding to $\tau_i \equiv 4m_i^2/m_h^2$ ($i = W, t, S$) refer to spin-1 (W boson), spin-1/2 (top quark) and charged spin-0 particles in the loop. Following [15] we define the enhancement factor with respect to the SM decay width

$$R_{\gamma\gamma} = \left| 1 + \sum_{S=\Phi^+,\Phi^-,\Phi^{--}} Q_S^2 \frac{c_S}{2} \frac{v_H^2}{m_S^2} \frac{A_0(\tau_S)}{A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)} \right|^2 . \tag{14}$$

This enhancement is dominated by the lightest charged scalar Φ^{--} and the value $R_{\gamma\gamma} = 2$ can be achieved up to $m(\Phi^{--}) = 280$ GeV, and the value $R_{\gamma\gamma} = 1.25$ up to $m(\Phi^{--}) = 520$ GeV.

	$\overline{\Sigma^{++}} \to \ell^- W^-$ (0.66)	$\overline{\Sigma^{+}} \to \ell^- Z^0$ (0.06)	$\Sigma^0 \to \ell^+ W^-$ (0.30)	$\Sigma^0 \to \ell^- W^+$ (0.30)
$\Sigma^{++} \to \ell^+ W^+$ (0.66)	$\ell^+\ell^- W^+ W^-$ (0.44)	$\ell^+\ell^- W^+ Z^0$ (0.04)	- -	- -
$\Sigma^{+} \to \ell^+ Z^0$ (0.06)	$\ell^+\ell^- Z^0 W^-$ (0.04)	$\ell^+\ell^- Z^0 Z^0$ (0.004)	$\ell^+\ell^+ Z^0 W^-$ (0.02)	$\ell^+\ell^- Z^0 W^+$ (0.02)
$\Sigma^0 \to \ell^- W^+$ (0.30)	- -	$\ell^-\ell^- W^+ Z^0$ (0.02)	- -	- -
$\Sigma^0 \to \ell^+ W^-$ (0.30)	- -	$\ell^+\ell^- W^- Z^0$ (0.02)	- -	- -

TABLE 3: Decays of exotic leptons to SM charged leptons, including multi-lepton and same-sign dilepton events, together with their branching ratios (restricted to $l = e, \mu$ and for $M_\Sigma = 400\,\mathrm{GeV}$).

Another loop mediated Higgs decay sensitive to new charged particles is $h \to Z\gamma$, where we obtain a moderate suppression of the $h \to Z\gamma$ decay rate in the region of the parameter space where the $h \to \gamma\gamma$ decay rate is enhanced.

4 Conclusions

The need for neutrino masses modifies the “old” SM to a “new νSM” where, in order to understand the lightness of active neutrinos, one commonly introduces new heavy degrees of freedom. While no evidence for such new particles has been found so far at the LHC, evidences from astrophysics and cosmology point at 23% of the energy density of the Universe provided by DM [16]. Notably, appealing DM candidates are heavy neutrino-like weakly interacting massive particles (WIMPs).

Bearing in mind an accidental stability of our ordinary matter, it is tempting to imagine a setup in which DM is also accidentally stable. The so-called minimal dark matter model (MDM) [17] is probably the simplest such scenario. In this setup the stability can be guaranteed for a neutral component of a large enough fermion or scalar $SU(2)_L$ multiplet, which can not form $SU(2)_L$ invariant renormalizable (or lowest nonrenormalizable, dimension-five) interaction-terms with the SM multiplets. For a fermion candidate it would be the quadruplet (quintuplet) and higher, and for a scalar candidate the sextuplet and higher. Since the neutral (DM) component cannot have the tree level interactions to the Z boson, both the hypercharge Y and the third isospin-component T_3 must vanish. This is possible only for odd multiplets: fermion quintuplet or higher, and scalar septuplet or higher.

When employing the fermion quintuplets as seesaw mediators, like in two models presented here, they are in conjunction with appropriate scalar quadruplets. This destroys the stability which the MDM Majorana quintuplet may possess in isolation.

By exploring the conditions under which the quintuplets $\Sigma_R \sim (1, 5, 0)$ could simultaneously generate neutrino masses and provide a stable DM candidate, the paper [18] raised the hope

that the Majorana quintuplet in conjunction with a scalar septuplet can do the job, leading to radiative neutrino mass mechanism (RνMDM) with an automatic Z_2 symmetry. However, we have demonstrated [19] that this is still not possible without imposing the discrete Z_2 symmetry by hand. This brings us back to the model [13] with a Majorana quintuplet and a scalar quadruplet as a more minimal option. The mass of Σ^0, as the DM particle protected by the Z_2 symmetry, is fixed by the relic abundance to the value [17] $M_\Sigma \approx 10$ TeV. The choice $\lambda_5 = 10^{-7}$ gives enough suppression to lead to small neutrino masses with large Yukawas, $Y \sim 0.1$. In this part of the parameter space the model could have interesting LFV effects like in [18].

Finally, we should keep in mind the possibility that DM may belong to a setup not very different from fine-tuned (anomaly-free) set of ordinary SM particles. A mere mismatch in the charges of the SM and DM particles explains a separate stability of two parallel worlds, and the adventure of explaining neutrino masses may for the first time reveal the charges of some of the DM species.

Acknowledgments

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